

DISTRIBUTIONS OF LARGE METEORIC BODIES

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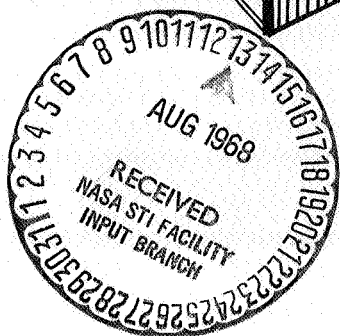
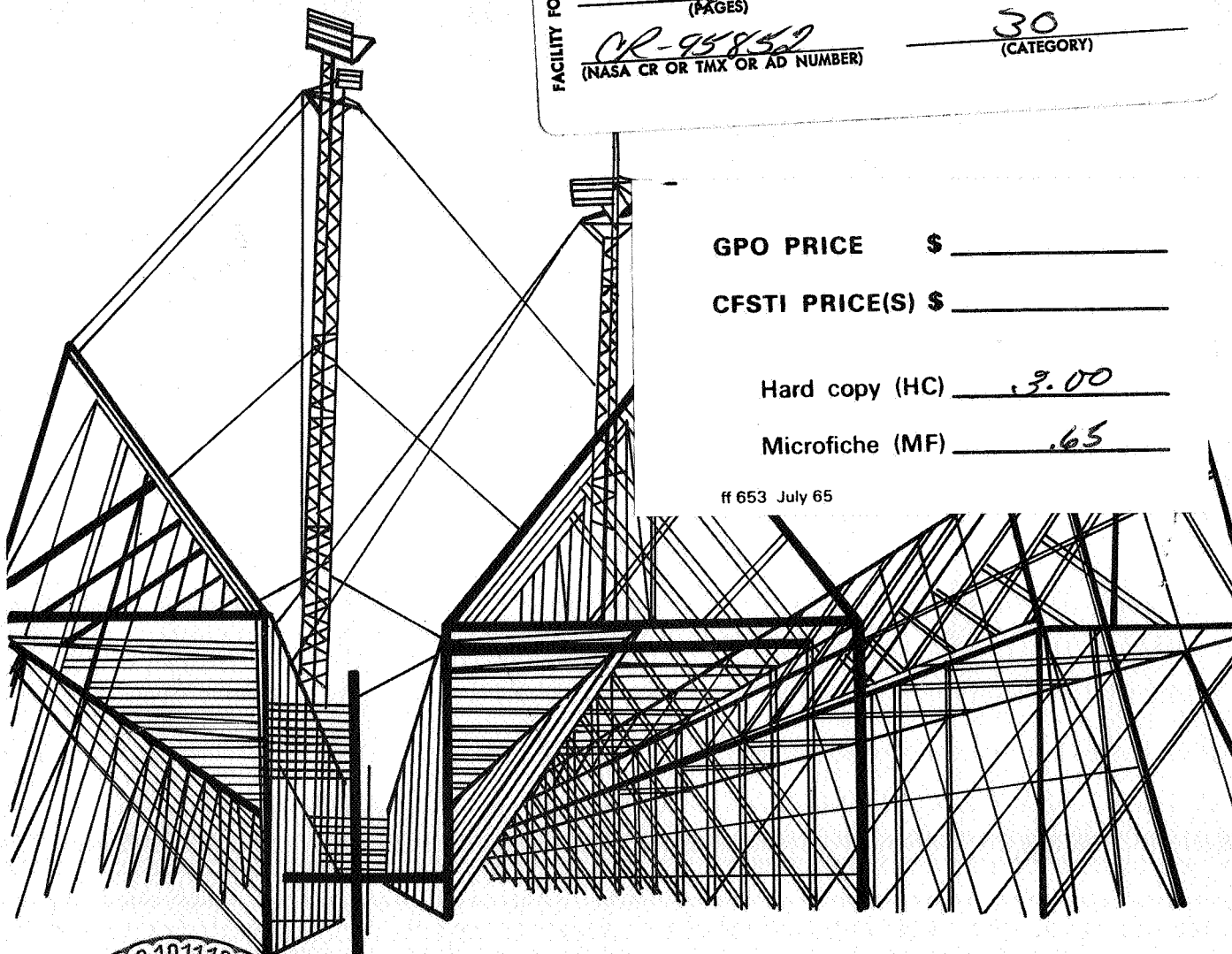
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THE DISTRIBUTION OF MAGNITUDES, MASSES, AND ENERGIES
OF LARGE METEORIC BODIES

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ABSTRACT

I have analyzed 82 Prairie Network meteors photographed between JD 2,439,000 and 2,439,500. Nearly all objects with $M \leq -9$ that occurred during that period are included. The photometric data permit a preliminary determination of the distribution function of magnitude, mass, and energy of bright meteors. The influx rate of the brightest objects is found to be high compared with the rate expected from an extrapolation of visual data. The mass influx, at the top of the atmosphere, exceeds that deduced from meteorite falls by 1 or 2 orders of magnitude.

RÉSUMÉ

J'ai analysé 82 météores photographiés par Prairie Network, entre les JJ 2.439.000 et 2.439.500. Presque tous les corps à magnitude $M \leq -9$, apparus pendant cette période de temps, ont été inclus. Les données photométriques permettent une détermination préliminaire de la fonction de distribution des magnitudes, masses, et énergies des météores brillants. Le taux d'arrivée des objets les plus brillants a été trouvé grand en comparaison du taux qui résulterait d'une extrapolation des données visuelles. L'arrivée des masses, au sommet de l'atmosphère dépasse d'un facteur 10 ou 100 celle déduite des chutes des météorites.

КОНСПЕКТ

Я произвел анализ 82 метеоров сфотографированных Сетью Прэри между JJ 2.439.000 и 2.439.500. Включены почти что все об'екты с $M \leq -9$ имевшие место за этот период. Фотометрические данные позволяют произвести предварительное определение функции распределения величин, масс и энергий ярких метеоров. Скорость притока наиболее ярких об'ектов была найдена высокой по сравнению со скоростью ожидаемой исходя из экстраполяции данных наблюдений. Приток массы на верхней границе атмосферы превышает на 1 или 2 порядка величины приток который был выведен из данных падений метеоритов.

THE DISTRIBUTION OF MAGNITUDES, MASSES, AND ENERGIES OF LARGE METEORIC BODIES

R. E. McCrosky

1. THE DATA

In the following, I present a preliminary analysis of the Prairie Network data acquired between Julian days JD 2,439,000 and 2,439,500 (August 27, 1965, to January 8, 1967). Most of the exceptionally bright objects ($M \leq -9$) photographed during this period of time have been reduced, although in some cases it is still necessary to utilize provisional values of meteor magnitudes and masses. Precise photometric information is currently available on 75% of the cases under discussion. The photometry has been accomplished by procedures described by McCrosky and Posen (1968).

The following assumptions, conventions, and approximations made in the analysis should be borne in mind:

A. The magnitudes are "panchromatic magnitudes" and have been defined in terms of A0 stars; i. e., an A0 star, whose visual or photographic magnitude is m , is assigned the same numerical value in the panchromatic scale.

B. Maximum magnitudes refer to the greatest intensity reached by a smoothed curve drawn through the meteor light curve (intensity-time plot); i. e., short-duration flares have been eliminated in order that the magnitudes can be more representative of the meteor and correspond more closely to the effect that might be observed by a visual observer.

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C. In those cases where photometry of the meteor has been completed, the masses have been determined from an equation of the form:

$$m = \frac{2}{\tau_0} \int \frac{I}{V^3} dt \quad , \quad M = -2.5 \log I \quad . \quad (1)$$

I choose for the luminous efficiency $\tau_0 = 10^{-19}$ (0 mag, cgs), a value believed to be valid for much fainter objects when they are photographed with emulsions that are sensitive only to $\lambda < 5500 \text{ \AA}$. (Verniani, 1967). The change in sensitivity of the observing system may involve corrections of a factor of 2 or 3, but not 10, to the meteor masses. Corrections required because both the form of the equation and the constant are invalid for extremely bright objects are also unknown. While there is no suggestion from existing spectrographic data that the light production by meteors differs substantially for objects as bright as $M = -10$ from those in the usual photographic region ($M \approx 0$), corrections of the order of a factor of 10, but not so large as a factor of 100, must be considered conceivable for objects much brighter than $M = -10$.

Equation (1) has been evaluated numerically. A local value of velocity determined from the distance traversed by the meteor between each pair of shutter breaks has been used. Since the velocity of some Prairie Network meteors decreases to as much as one-third its initial value in the course of its trajectory, the masses are occasionally substantially higher than those obtained under the usual assumption that the meteor velocity is constant.

D. In some few cases the condition of the trajectory or of the atmosphere through which the meteor was seen was such that no detailed photometry was possible. In these cases, I have estimated the brightness at maximum light and at each extreme of the trajectory. The light curve (magnitude versus time) is then assumed to consist of two parabolas defined by the values at maximum light and one extreme and by the condition $(dM/dt)_{\max} = 0$. This analytical light curve and equation (1) are used to determine the mass.

E. In those cases (about 25%) where only provisional values of photometry are available, the mass estimates are derived from a simplified equation of the form

$$m \text{ (kg)} = \frac{18.5 T \exp (-0.92 M)}{V^3 \sqrt{\Delta M}} \quad . \quad (2)$$

This equation, again based on a light curve composed of two parabolas, is strictly valid if the velocity V (10 km/sec units) is constant throughout the trajectory and if ΔM , the difference in magnitude between maximum light and the film limit, is the same for both extremes of the meteor trail. The duration of the meteor is represented by T (sec).

2. CUMULATIVE DISTRIBUTIONS OF MAGNITUDE, MASS, AND ENERGY

The distributions will be forced to fit a cumulative distribution law of the form

$$\log N(X) = a + b \log X \quad ,$$

where N is the number of events per square centimeter per second equal to or exceeding some limit X . This equation can adequately describe our data, but since it is a mathematical device and contains no physics, extrapolations beyond the limit of the data are essentially meaningless. Two distinct problems are involved in this equation: One concerns the magnitude of the event, and the other, the effective coverage of the system that observed it. Since the events are vastly brighter than any known source that is being observed through the same optical system (and, indeed, in many cases so bright that they greatly exceed the useful dynamic range of the system), errors in the measurement of the fundamental quantity, the meteor magnitude, may be as high as 2 or 3 mag. Probable errors of 0.5 mag are more usual. While this value is inferior to the results obtained for more ordinary meteors, where errors of 0.2 mag are obtainable, it is nevertheless superior to that obtainable by visual techniques.

The coverage of a two-station network can easily be computed from actual operation times. For a very large network — particularly one in which a large number of stations patrol each element of the area under observation — the coverage can be estimated from quite general considerations of the optical properties of the camera, the meteorological statistics of the region, and the operating statistics of the network. The Prairie Network, with 16 stations, lies between the extremes of easily computed and safely estimated coverage. The computational approach has been chosen. A computer program has been prepared to determine the total coverage

of the Network, in units of area-time, for meteors of brightness M . The program performs as follows: For a meteor of a given brightness, each camera has under observation certain cells of area at the 60-km height. The cells depend not only on meteor brightness but also on the atmospheric absorption, the meteor range, and the vignetting properties of the optics. Other cameras in the Network may or may not have one of these cells under observation as well. If a particular cell can be observed by at least two cameras and if the two cameras have been operating without instrumental or meteorological interference, the area of this cell, multiplied by the time the cameras are operating (or the probable time they operated simultaneously), represents the coverage supplied by that cell during that night. The sum of all such cells determines the coverage for meteors of brightness M for that night. The computation is made for integer magnitudes from -5 to -9 (objects brighter than -9 are always sufficiently bright to be photographed so long as their zenith distance is not greater than 80°). The input for this machine program is derived from an inspection of the film. Each frame from each camera is assigned an effective exposure time, and the sum of the exposures for the entire night is used as the time factor in the coverage program for that camera. An hour's difference exists between the eastern- and western-most portions of the Network. A correction for the lack of simultaneity in the observations (as a function of time of year) is included in the program.

For the period JD 39000 to 39500 and for bright objects ($M < -8.7$), the total coverage C has been $1.3 \times 10^{23} \text{ cm}^2 \text{ sec}$. Table 1 presents weights suggested by the coverage computations for meteors of magnitude M . All subsequent plots are derived from data weighted according to this scheme.

2.1 Distribution of Maximum Magnitudes

All previous determinations of the distribution of bright meteors have depended on visual observations. Observations of objects with $M < -10$ are nonexistent in the visual data. Neither the magnitude estimates nor the corrections for coverage, made difficult by the variable effective field of the observers' eye as a function of object brightness, can be made with the

precision supplied by the optical observations. Either the errors in the visual observations or, more likely, the danger of extrapolating these data to extreme limits can be demonstrated by reference to Millman's work (1957). McKinley (1961) has reassessed Millman's data, and after applying a correction to the total number of meteors brighter than $M_V = -5$ derived by Hawkins and Upton (1958), he found $\log N \approx -17.7 + 0.57 M_V$ ($-10 \leq M_V \leq 0$, number/cm² sec). If this equation were used to predict the number of objects of photographic magnitude $M_p = -18$ ($M_V = -16$), we would conclude that $C = 10^{27}$ cm² sec was required. However, one such object was observed in the Prairie Network in the 500-day period with $C = 1.3 \times 10^{23}$ cm² sec. Furthermore, Ceplecha's two-station Czechoslovakian program recorded the Příbram meteorite, at $M_V = -19$, with $C \approx 10^{22}$ cm² sec (Ceplecha, 1961), and the Czechoslovakian multistation fireball network has recorded an object of $M_V = -17$ with comparable coverage (Ceplecha, 1967). The brightest Prairie Network object is not a statistical freak.

Table 1. Weighting function for meteors of brightness M photographed by the Prairie Network

M_{pan}	W
-5.0	3.40
-5.5	2.90
-6.0	2.45
-6.5	2.10
-7.0	1.75
-7.5	1.50
-8.0	1.30
-8.5	1.10
<-8.7	1.00

The cumulative distribution of magnitudes among the 82 Prairie Network objects is shown in Figure 1. The best-fit line, drawn by eye, is represented by the equation

$$\log N = -19.4 + 0.22 M_{\text{pan}} .$$

On the same graph, we display McKinley's curve representing an extrapolation of the bright visual observations. A constant color index,

$$\text{C.I.} = M_{\text{pan}} - M_{\text{v}} = -2.0 ,$$

has been assumed to convert the visual magnitude to panchromatic magnitude.

2.2 Distribution of Preatmospheric Masses and Kinetic Energies

The number of cases of mass greater than m (g), as determined from photometry and from equation (1) or (2), is shown in Figure 2 as a function of mass. The line is represented by the equation

$$\log N(m) = -19.1 - 0.62 \log m \text{ (g)} .$$

For comparison, we show three curves (from Whipple, 1967) that were derived from optical meteor data and meteorite-fall data. The line labeled "meteors" represents a considerable extrapolation from the mass range $(-3 < \log m < 0)$ for which the curve was derived. The distributions labeled "meteorites" are estimates of the preatmospheric mass, obtained by correcting the found mass for ablation by a factor of 5. No correction has been applied for any diurnal effect in meteorite falls. Since the fall rate is reduced during the dark hours when photographic coverage is possible, the fluxes implied by the meteorite curves are upper limits when used in comparison with the Network data.

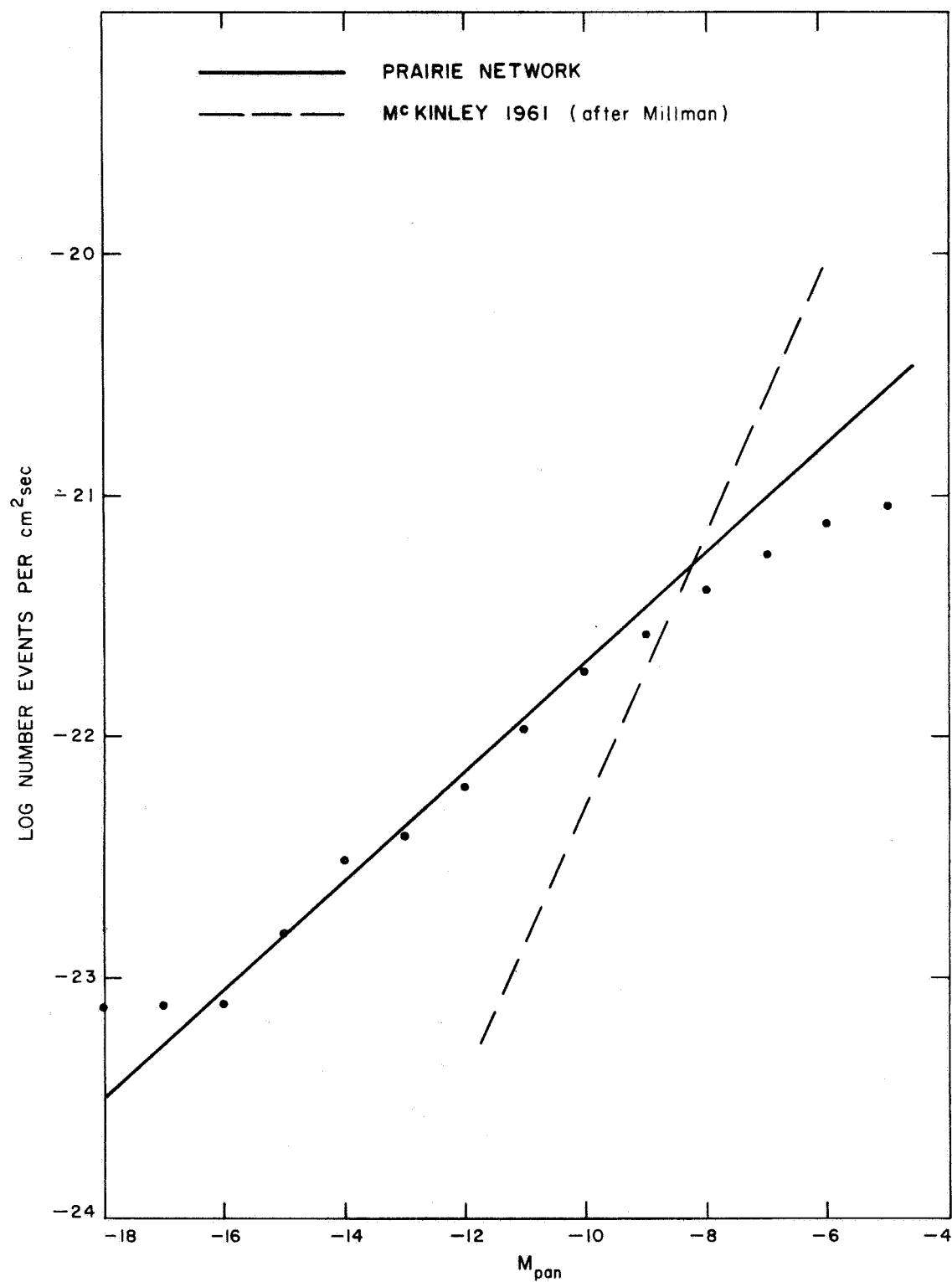


Figure 1. Cumulative distribution of bright-meteor magnitudes.

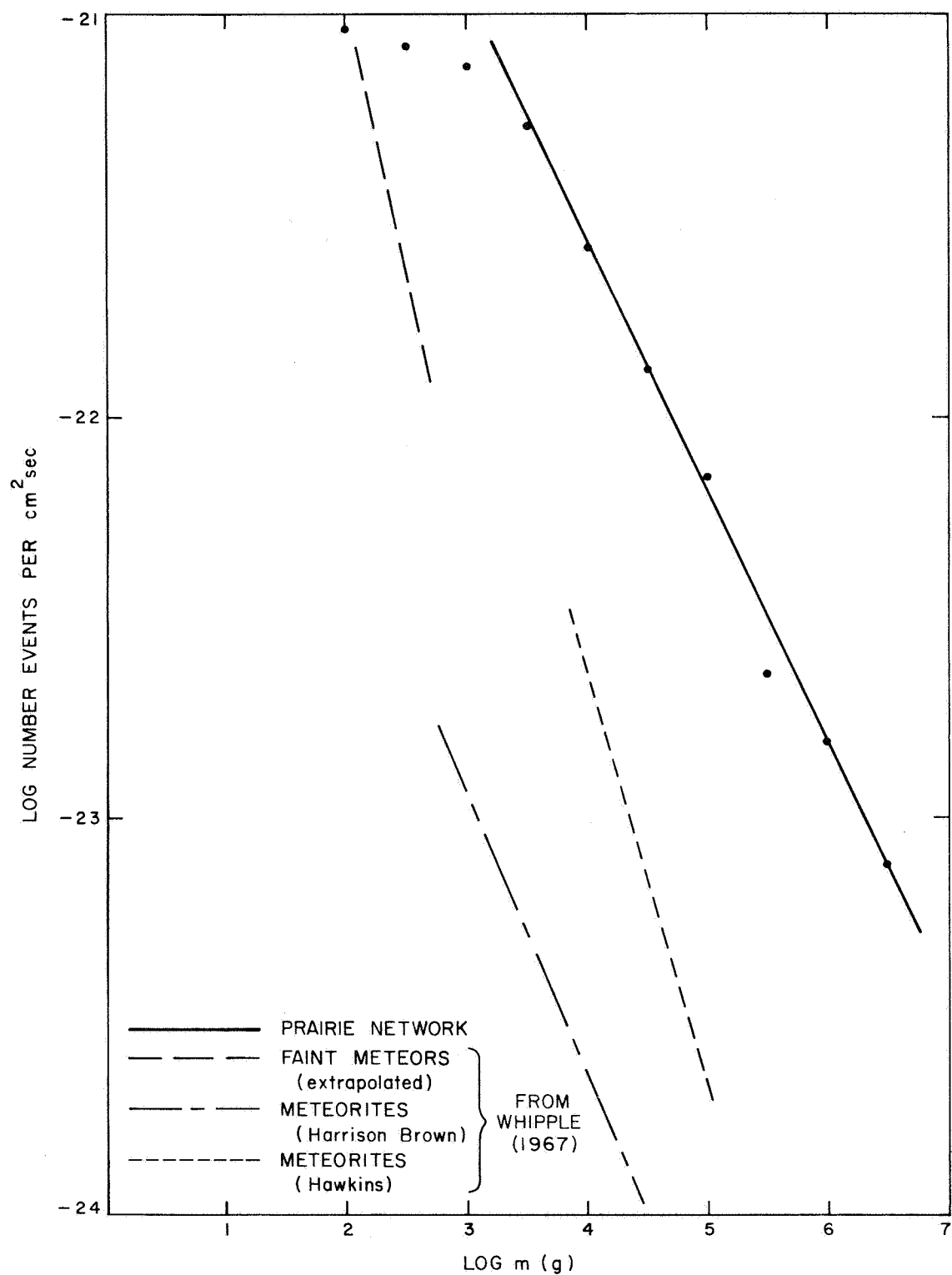


Figure 2. Cumulative distributions of preatmospheric masses.

In Figure 3, we give a similar distribution for the energy flux of Prairie Network meteors, where the energy is defined as the kinetic energy of the preatmospheric meteoroid,

$$E = \frac{1}{2} m v_{\infty}^2 \quad .$$

Here, m is the photometric mass, and v_{∞} is the preatmospheric velocity. The cumulative distribution is given by

$$\log N(E) = -10.5 - 0.67 \log E \text{ (ergs)} \quad .$$

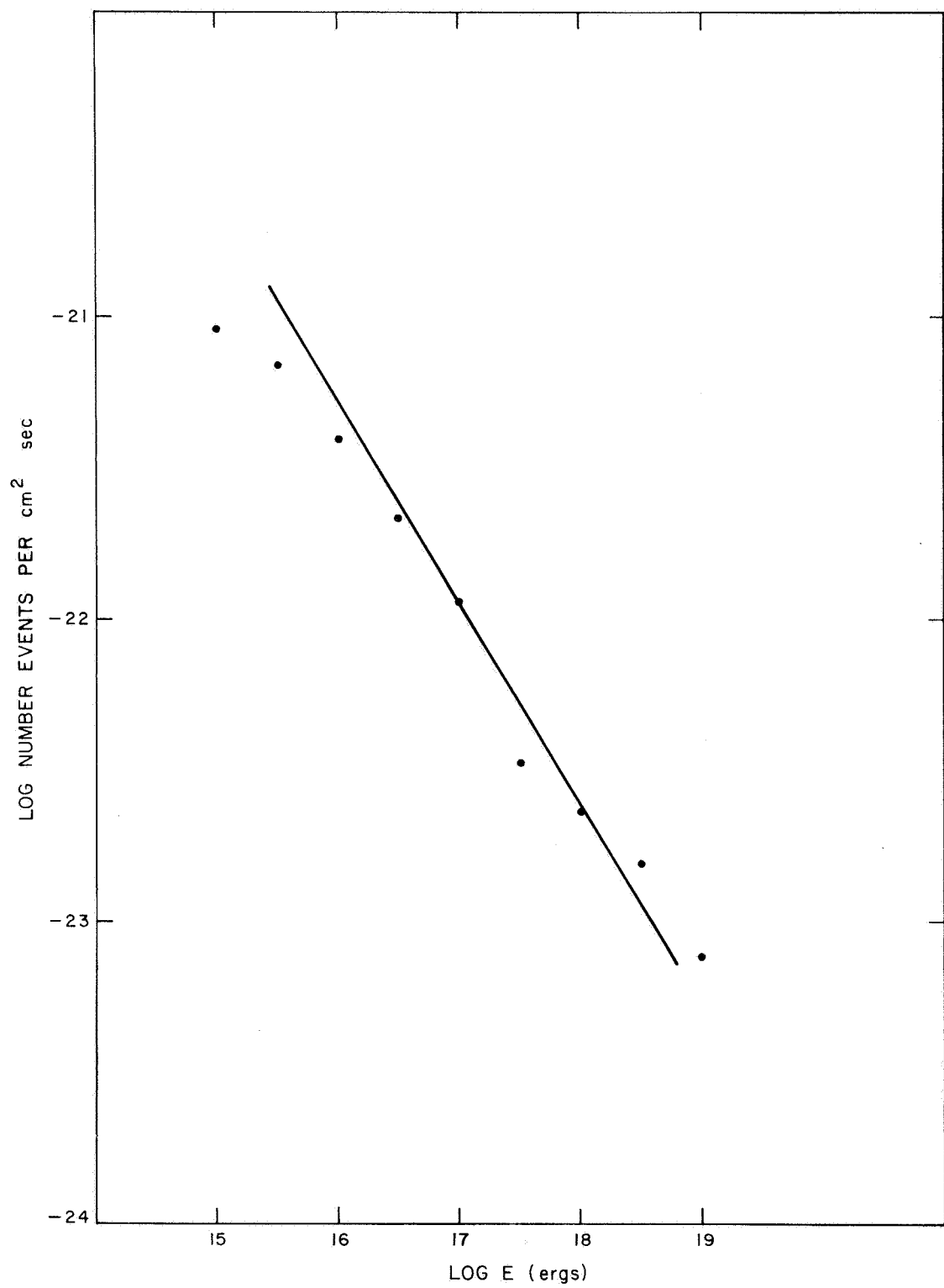


Figure 3. Cumulative distribution of kinetic energy of meteoroids outside the atmosphere.

3. INTERPRETATION

While the details of this preliminary analysis are subject to change, the principal result (shown in Figure 1), that bright meteors occur far more frequently than was previously thought, is beyond dispute. We have chosen to compare this with the Millman-McKinley curve, since these are the only other data for which an estimate of coverage has been made. The difference of the slopes of the visual and of the Prairie Network curves would have been less striking had we used either the American Meteor Society data or the British Astronomical Association data (see Hawkins and Prentice, 1957), where a slope of 0.4 has been suggested; but even this lower value cannot be used to represent the Prairie Network data. It should be noted that there is not necessarily any great discrepancy between the visual and the bright photographic material. The visual data purport to extend to objects only as bright as -8 or -10 mag, and the Prairie Network material is complete only at magnitudes brighter than that. (A large number of meteors as bright as -7 or -8 with durations of less than 1 sec exist in our unreduced material and account for the decrements between the observed numbers of small, faint objects and the proposed linear distributions of Figures 1 to 3.)

The mass influx lies between 1 or 2 orders of magnitude above all previous estimates, but before accepting these results at face value, we should recall the uncertainties in the luminous efficiency τ_0 that was used to derive these results. In particular, if the luminous efficiency increases with event brightness, the abnormal numbers of both bright and massive meteors can be explained. However, the luminous efficiency used corresponds to about 0.1% of the kinetic energy being converted to light in the photographic region, and we can set some extreme limits on the mass flux by assuming 100% efficiency. Such a drastic revision would displace the observed mass curve (Figure 2) only as far left as Brown's meteorite curve. It would seem that a 1% efficiency would represent a more reasonable upper limit to this quantity, in which case objects of 10^5 g are occurring at a frequency at least 10 times that predicted on the basis of meteorite finds.

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BIOGRAPHICAL NOTE

RICHARD E. McCROSKY received his B. S. degree in physics from Harvard University in 1952 and his Ph. D. in astronomy from that university in 1956.

Dr. McCrosky holds joint appointments as Astronomer, Smithsonian Astrophysical Observatory, and Research Associate, Harvard University. He is also Scientist-in-Charge of the Smithsonian's optical meteor projects. His primary research specialties include photographic and spectral meteor studies.

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